Measured Propagation Characteristics of Coplanar Waveguide on Semi-Insulating 4H-SiC Through 800 K

George E. Ponchak, *Senior Member, IEEE*, Samuel A. Alterovitz, Alan N. Downey, Jon C. Freeman, and Zachary D. Schwartz

***Abstract*—Wireless sensors for high temperature industrial applications and jet engines require RF transmission lines and RF integrated circuits (RFICs) on wide bandgap semiconductors such as SiC. In this paper, the complex propagation constant of coplanar waveguide fabricated on semi-insulating 4H-SiC has been measured through 813 K. It is shown that the attenuation increases 3.4 dB/cm at 50 GHz as the SiC temperature is increased from 300 K to 813 K. Above 500 K, the major contribution to loss is the decrease in SiC resistivity. The effective permittivity of the same line increases by approximately 5% at microwave frequencies and 20% at 1 GHz.**

***Index Terms*—Coplanar waveguide, propagation characteristics, SiC, transmission line.**

I. INTRODUCTION

HIGH-TEMPERATURE, high-frequency characterization of microwave transmission lines on wide bandgap semiconductors is required to design wireless circuits for applications where the ambient temperature is greater than 500 K, such as in aircraft engines. However, there are limited results reported in the literature. The attenuation of Coplanar Waveguide (CPW) on quartz, GaAs, and high resistivity Si has been shown to increase by 1, 3, and 5 dB/cm, respectively, at 10 GHz as the temperature is increased from 300 to 423 K [1], but these substrates are not suitable for high temperatures. Open-ended coaxial probes have been used to measure the complex permittivity of Al_2O_3, sapphire, and other materials from 300 to 1300 K [2], [3], but SiC has not been characterized with the coaxial probe. The resistivity of vanadium doped, semi-insulating 4H-SiC has been measured from 500 to 950 K with four point probe and Hall effect measurement system [4]–[6] and shown to decrease from 10^6 to 10^4 Ωm over the temperature range. Finally, the authors have reported that the attenuation of CPW on 4H-SiC increases by 3.2 dB/cm at 50 GHz as the temperature is increased from 300 K to 800 K [7].

In this paper, for the first time, the resistivity of metal lines and the attenuation of CPW lines on semi-insulating 4H-SiC over the temperature range of 300 to 813 K are reported. The attenuation is analyzed to determine the effects of the increase in metal line resistivity and the decrease of the SiC resistivity as the temperature is increased. The CPW effective permittivity is reported over the same temperature range.

II. CIRCUIT AND SUBSTRATE DESCRIPTION

A semi-insulating 4H-SiC substrate with a thickness of 409 μm and a room temperature resistivity greater than 10^5 Ωcm is used [8]. Before processing, an RCA clean is performed. No insulator is purposely grown on the SiC before or after processing. Finite width ground plane CPW lines with a center conductor width, slot width, and ground plane width of 50, 25, and 150 μm respectively are fabricated on the SiC using a liftoff process. The CPW lines consist of 20 nm of Ti and 1.5 μm of evaporated Au. CPW lines of 5000, 5850, 6700, 8500, and 17 500 μm lengths are used for the measurements.

III. MEASUREMENT PROCEDURE

A specially designed RF probe station capable of measurements through 813 K [9] was used to measure the CPW propagation characteristics. Before measurements of the CPW lines, the system was characterized as a function of temperature and the temperature dependence was subtracted from the measured results prior to analysis. At room temperature, a TRL calibration was performed using the full set of CPW lines described above and implemented with the NIST MULTICAL software [10]. At each temperature from 300 to 813 K, the 17 500 μm long CPW line was measured, from which the insertion loss is determined. The increased loss and phase due to the CPW thru line length as the temperature was increased was subtracted from the reported results.

IV. RESULTS

The dc resistivity of the 50 and 150 μm wide, Ti/Au evaporated lines that comprise the CPW transmission line were measured as a function of temperature. The measured resistivity increases from 3 $\mu\Omega$cm to 8.75 $\mu\Omega$cm as the temperature is increased from 300 to 800 K. If the published resistivity of

Manuscript received March 31, 2003; revised July 9, 2003. This work was sponsored by the Ultra-Efficient Engine Technology program at NASA Glenn Research Center. The review of this letter was arranged by Associate Editor Dr. Rüdiger Vahldieck.

G. E. Ponchak, S. A. Alterovitz, A. N. Downey, and J. C. Freeman are with NASA Glenn Research Center, Cleveland, OH 44135 USA (e-mail: george.ponchak@ieee.org).

Z. D. Schwartz is with Analex Corporation, NASA Glenn Research Center, Cleveland, OH 44135 USA.

Digital Object Identifier 10.1109/LMWC.2003.819373

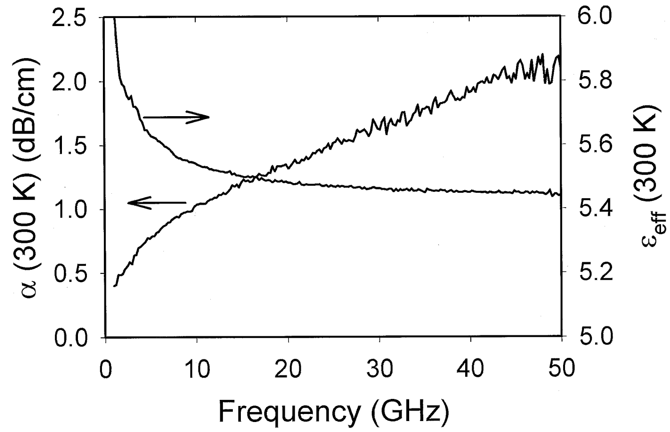

Fig. 1. Measured attenuation and effective permittivity of CPW line on SiC at room temperature (300 K).

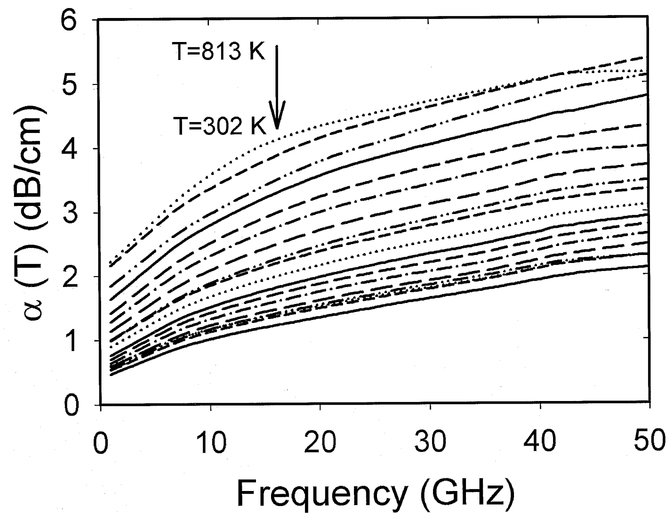

Fig. 2. Measured attenuation of CPW line on 4H-SiC over the temperature range of 302 to 813 K.

bulk gold [11] is multiplied by an empirically found correction factor of 1.29, which corrects for the Ti adhesion layer and metal roughness, the measured and published resistivity agrees to within 2% across the 500 K temperature range. Although the data is fit by a second-order polynomial, to within 2% error, the resistivity increases linearly with temperature.

The room temperature characteristics of the CPW line are shown in Fig. 1. The low attenuation (2.2 dB/cm at 50 GHz) and the $\sqrt{f}$ frequency dependence indicate that room temperature attenuation is due to conductor loss. Qualitatively, the measured effective permittivity, ε_{eff}, is typical of thin film transmission lines, with a high value at low frequency due to internal inductance in the metal lines and decreasing to the quasistatic value. Using the quasistatic approximation that $\varepsilon_{\text{eff}} = (\varepsilon_r + 1)/2$, the 300 K relative permittivity, ε_r, of the SiC is found to be 9.8, which agrees with published value of 9.7 [12].

The measured attenuation as a function of frequency over a temperature range of 300 to 813 K is shown in Fig. 2, and the measured increase in attenuation as a function of temperature is shown in Fig. 3. It is seen that the attenuation increases 1.7 dB/cm at 1 GHz, 3.0 dB/cm at 25 GHz, and 3.4 dB/cm at

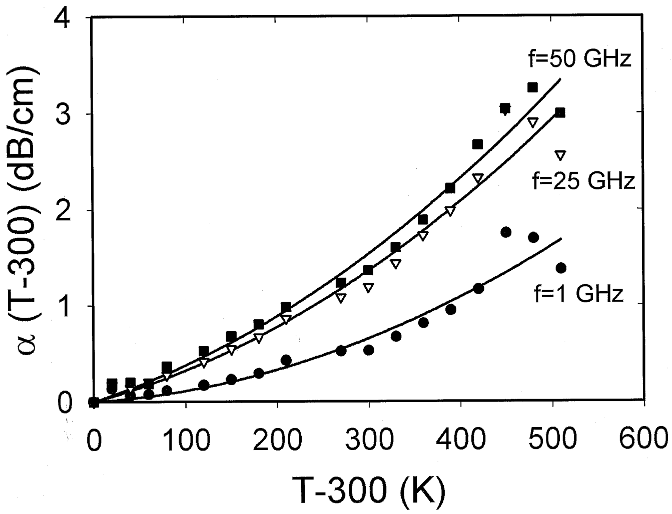

Fig. 3. Measured increase in attenuation of CPW lines on SiC as a function of temperature.

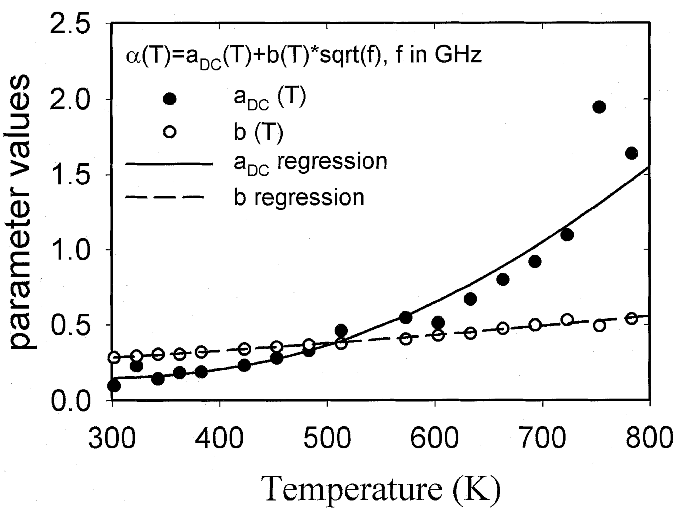

Fig. 4. Deembedded fitting parameters for attenuation of CPW lines on SiC.

50 GHz when the temperature is increased by 500 K. If the attenuation is assumed to be described by

$$\alpha(f) = a_{\text{dc}} + b\sqrt{f} \tag{1}$$

which is usually valid for room temperature CPW lines on insulating substrates, the fitting parameters a_{dc} and b are shown in Fig. 4. The parameter a_{dc} is comprised of two components. The first is the I^2R loss through the metal lines, which, to a first approximation, varies linearly with temperature. The second is the dielectric loss due to the noninfinite resistivity of the SiC. To a first order approximation, the SiC resistivity and the dielectric attenuation varies with temperature as $e^{-Ea/kT}$ [13], where E_a is an effective activation energy measured in eV. Combining these two parts of the loss at zero frequency and fitting the values shown in Fig. 4, it is found that

$$a_{\text{dc}} = 4.332 \cdot 10^{-4}T + 26.05e^{-0.22/kT} \tag{2}$$

where T is in Kelvin and k is Boltzmann's constant. E_a agrees with the accepted value of 0.2 for p type dopants in 4H-SiC

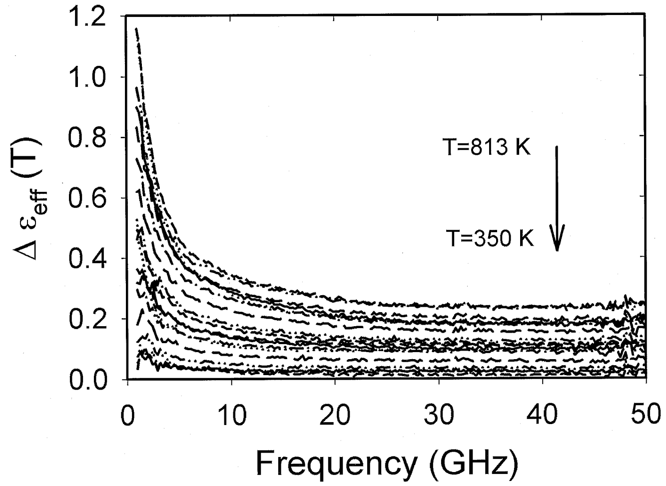

Fig. 5. Measured change in effective permittivity of CPW lines on SiC as a function of temperature and frequency.

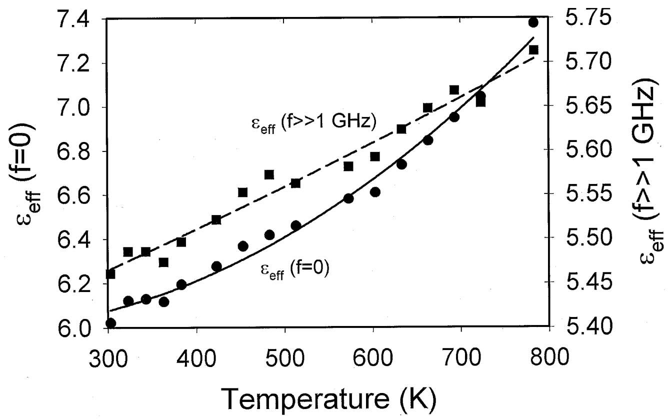

Fig. 6. Measured effective permittivity of CPW lines on SiC as a function of temperature.

[12]. An E_a of 0.2 indicates that the semi-insulating 4H-SiC is not counter doped with vanadium, which yields E_a of 0.8 to 1.8 [4]–[6]. Lastly, (2) shows that the large increase in low frequency attenuation above 500 K is primarily due to the reduction in the SiC resistivity.

The fitting parameter b should vary as $\sqrt{T}$ if the resistivity varies linearly with temperature and the metal thickness is large compared to the skin depth, δ_s. However, the 1.5 μm thick metal lines are three times δ_s at 30 GHz at 300 K and 48 GHz at 473 K. Thus, over most of the temperature and frequency range reported in this paper, the thick metal approximation is not valid, and the attenuation shown in Fig. 2 and the values of b shown in Fig. 4 confirm this. However, if only the attenuation above 30 GHz is fit to (1), b is found to vary as the $\sqrt{T}$ as expected for $T < 473$ K.

The measured change in $\varepsilon_{\rm eff}$ as a function of frequency is shown in Fig. 5, and summarized in Fig. 6 as a function of temperature. At low frequency, $\varepsilon_{\rm eff}$ varies as a second-degree polynomial and increases by 21% as temperature is increased from 300 to 800 K. The second-degree polynomial variation indicates an increase in the internal inductance of the metal lines, which increases $\varepsilon_{\rm eff}$. At high frequency, $\varepsilon_{\rm eff}$ increases by only 5%.

V. Conclusion

The first analysis of the propagation characteristics of a CPW on semi-insulating SiC over a large temperature range has been presented. The metal resistivity is linearly dependent on temperature, but the decrease in SiC resistivity as the temperature increases is shown to be the major contributor to the increase in attenuation, which can be as high as 3.4 dB/cm. The effective permittivity increases by 21% at low frequency. These results indicate that thicker metal is required to reduce attenuation and dispersion in high temperature RFICs, but that the increase in attenuation is not significant and the dispersion above 5 GHz can be accounted for in circuit designs.

References

[1] A. C. Reyes, S. M. El-Ghazaly, S. Dorn, and M. Dydyk, "Temperature and bias effects in high resistivity silicon substrates," in *1996 IEEE MTT-S Int. Microwave Symp. Dig.*, June 17–21, 1996, pp. 87–90.

[2] S. Bringhurst, M. F. Iskander, and M. J. White, "Thin-sample measurements and error analysis of high-temperature coaxial dielectric probes," *IEEE Trans. Microwave Theory and Tech.*, vol. 45, pp. 2073–2083, Dec. 1997.

[3] D. L. Gershon, J. P. Calame, Y. Carmel, T. M. Antonsen Jr., and R. M. Hutcheon, "Open-ended coaxial probe for high-temperature and broad-band dielectric measurements," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 1640–1648, Sept. 1999.

[4] R. C. Clarke, C. D. Brandt, S. Sriram, R. R. Siergiej, A. W. Morse, A. K. Agarwal, L. S. Chen, V. Balakrishna, and A. A. Burk, "Recent advances in high temperature, high frequency SiC devices," in *Proc. 1998 High-Temperature Electronic Materials, Devices, and Sensors.*, San Diego, CA, Feb. 22–27, 1998, pp. 18–28.

[5] S. T. Allen, W. L. Pribble, R. A. Sadler, T. S. Alcorn, Z. Ring, and J. W. Palmour, "Invited-progress in high power SiC microwave MESFETs," in *IEEE MTT-S Int. Microwave Symp. Dig.*, June 13–19, 1999, pp. 321–324.

[6] J. R. Jenny, J. Skowronski, W. C. Mitchel, H. M. Hobgood, R. C. Glass, G. Augustine, and R. H. Hopkins, "Deep level transient spectroscopic and Hall effect investigation of the position of the vandium acceptor level in 4H and 6H SiC," *Appl. Phys. Lett.*, vol. 68, no. 14, pp. 1963–1965, Apr. 1996.

[7] G. E. Ponchak, Z. D. Schwartz, S. A. Alterovitz, A. N. Downey, and J. C. Freeman, "Temperature dependence of attenuation of coplanar waveguide on semi-insulating 4H-SiC through 540°C," *Electron. Lett.*, vol. 39, no. 6, pp. 535–536, Mar. 20, 2003.

[8] *Cree wafer number BV0302-11, Part Number W4TRD8R-0D00.*

[9] Z. D. Schwartz, A. N. Downey, S. A. Alterovitz, and G. E. Ponchak, "High-temperature probe station for use in microwave device characterization through 500°C," in *Proc. 61st ARFTG Microwave Measurements Conf. Dig.*, Philadelphia, PA, June 13, 2003.

[10] R. B. Marks, "A multiline method of network analyzer calibration," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 1205–1215, July 1991.

[11] D. R. Lide, Ed., *Handbook of Chemistry and Physics*, 73rd ed. Boca Raton, FL: CRC, pp. 12–34.

[12] P. G. Neudeck, *The VLSI Handbook*, W.-K. Chen, Ed. Boca Raton, FL: CRC, 2000, pp. 6–3.

[13] S. M. Sze, *Physics of Semiconductor Devices*. New York: Wiley, 1981, pp. 22–31.